The Development and Operation of Low-cost Reedbeds for Greywater Treatment in Costa Rica, Central America

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Abstract
In rural Costa Rica it is widespread practice to separate greywater from blackwater (toilet water), with only the blackwater connected to a septic system. The flow of untreated greywater directly into the environment is a cause of substantial environmental contamination and poses a significant health risk. Low cost reedbeds for the treatment of domestic greywater in Monteverde, Costa Rica were developed in order to achieve affordable, low maintenance systems. A range of design and installation modifications relevant to the local environment were developed in order to achieve this objective as well as to meet the national guidelines for wastewater reuse. The use of PET plastic segments was found to be a viable alternative media to gravel and its potential as a readily available material which can significantly reduce the cost of reedbeds is described. This paper summarises the experience gained from over four years in terms of the design, installation, affordability, performance and maintenance of reedbeds for greywater treatment in the mountainous tropics of Central America.

Keywords
Reedbeds, greywater, constructed wetlands, appropriate technology, developing country

INTRODUCTION

Monteverde, located in the Tilaran mountain range of northwest Costa Rica, suffers from a lack of municipal planning and enforcement of national planning codes. As a result nearly all household greywater is discharged untreated directly into the town's streets and streams presenting a serious environmental and public health issue. Only blackwater (toilet water) receives any form of treatment via septic tanks which, like the majority of septic systems in Costa Rica, are poorly designed and constructed (Rosales, 2003). Monteverde is situated at an altitude of 1,300 metres above sea level and has a tropical montane climate.

The objective of this paper is to summarise our research over four years into the development of low-cost reedbeds for domestic greywater treatment in terms of design features, operation and maintenance.

CONSTRUCTED WETLANDS FOR WATEWATER TREATMENT

The potential for constructed wetlands (CWs) in developing countries for wastewater treatment and reuse is described as enormous (Denny, 1997; Haberl, 1999). This assessment was made on the basis of their low cost and ease of operation and maintenance when compared to conventional treatment systems, and that they represent an appropriate and sustainable technology for wastewater treatment – properties which have been widely documented. Constructed wetlands are also particularly well suited to small towns and rural communities where sufficient land is more likely to be available (Green, Griffin et al., 1997). The warm tropical and subtropical climates found in many developing countries are ideal for productive biological systems such as constructed wetlands and yet the spread of this technology has been described as depressingly slow (Denny, 1997). Kivaisi (2001) concluded that in developing countries "these systems have not found widespread use, due to lack of awareness and local expertise in developing the technology on a local basis".

Subsurface flow (SSF) wetlands, also known as reedbeds, have the advantage of avoiding odour, mosquitoes and public contact as the water level is maintained below the media surface, as well as a smaller land area requirement compared to free water surface (FWS) wetlands (Kadlec and Knight, 1996). The health issues associated with creating potential mosquito habitat are significant in developing countries such as Costa Rica where malaria and dengue fever are prevalent (PAHO, 2001). Disadvantages however include the potential for inlet clogging and the cost of the substrate media which may be of the order of 50% of the total construction cost (USEPA, 2000). No documented prior experience with reedbeds for wastewater treatment in Costa Rica exists (Rosales, 2003) although reedbeds (*biofiltros*) have been used successfully in neighbouring Nicaragua for the treatment of primary treated domestic sewage (Platzer and Cáceres, 2002).

Pathogen removal, as indicated by fecal coliform levels, in SSF wetlands is generally recognized as being superior to that of FWS wetlands (Kadlec and

Knight, 1996). Research by Green, Griffin et al. (1997) confirmed the ability of reedbeds to achieve 2 log removal of *E.Coli* and coliforms at retention times of 24 hours or more. Fecal coliform removal rates of >99% are typical in satisfactorily designed and operated systems however it is worth noting that these removal rates may still not be sufficient necessarily to achieve limits for wastewater reuse such as <1000 fecal coliform units/100ml (WHO, 1989; Hench, Bissonnette et al., 2003). The Costa Rican guidelines for wastewater reuse are fecal coliform < 1,000 cfu/100mL and BOD < 40 mg/L for restricted reuse and fecal coliform < 100 cfu/100 mL for unrestricted reuse (MdS, 1997).

Design Philosophy

It has been stated that, "For a technology to be applicable, beyond academic interest, it must be at least as cost effective as existing technologies" (Batchelor and Loots, 1997). The principal philosophy guiding this research was the design of affordable reedbed systems for the treatment of domestic greywater. In addition to cost, it was considered equally important that these systems could be built and maintained over the longterm by the owner. While Costa Rica has the highest per capita income (US$13,589) in Central America (MDG, 2003), monthly average salaries in rural areas such as Monteverde were typically $400-500/month in 2000. The cost in 1990 to install a reedbed (30-36 m^2) for a single household in the US for example was estimated at between US$2,000 and US$4,000 depending upon the amount of work done by the home owner (Steiner and Combs, 1993). The theoretical direct translocation of this technology to rural Costa Rica would therefore represent some four to five months salary – local uptake would be extremely low as a result. Cost considerations alone therefore required the use of low-cost, locally available materials and installation that would not require skilled labour if possible. For simple installation and in order to be low maintenance, it was necessary that all systems were gravity flow only (no pumps) with no complex plumbing or pipe fittings.

The Costa Rican guidelines for wastewater reuse (MdS, 1997) place emphasis on pathogen removal as does the Pan American Health Organisation's Wastewater Treatment and Reuse Program (OPS/CEPIS, 2002) which promotes the "implementation of appropriate technologies for pathogen removal rather than organic matter removal only". These guidelines were therefore adopted as the design criteria for treatment performance, and as no other national requirement was applicable. As a result hydraulic retention time (HRT) becomes the dominant design criterium. The potential for achieving a treated wastewater suitable for reuse was also considered highly desirable.

METHODS

The largest of the five systems installed in the Monteverde area as part of this research is described briefly followed by a summary of the resulting technology developments in terms of design considerations, operation and maintenance.

The four-household reedbed system for greywater treatment has been described previously (Dallas, Scheffe et al., In press) and only pertinent features are presented here. The system consists of two reedbeds in series followed by a pond and soakage area after which any surplus treated water overflows to a nearby stream. The reedbeds were sized according to an estimated design flow of 2,500 L/day maximum with a minimum hydraulic retention time (HRT) of two days. Subsequently one of the participating homes changed ownership and while three houses (seven people total including one child under 12 months of age) are still connected the total estimated greywater volume was reduced to approximately 755 L/day. This implied a revised retention time of 7.9 days total (4.5 days for reedbed one, 3.4 days for reedbed two). The first reedbed is 14m long, 1.2m wide and 0.6m deep (16.8m^2) and the second, approximately oval in shape, 6m by 3m and 0.6m deep (13m^2). The locally available crushed rock (20mm nominal diameter) was determined to have a porosity of 40%.

The performance of the system was demonstrated in terms of fecal coliform, BOD and turbidity removal across all seasons over three years and is presented in Table 1. Fecal coliform concentrations were determined by filtration followed by incubation in m-Endo agar LES for 24 hours at 44.5°C; turbidity was determined with a Hach 2100P portable turbidimeter and BOD was measured with a HACH 137 manometric unit according to APHA Standard Methods (1992).

Funding was achieved through a competitive environmental grant and the system was installed in 2001 at a cost of approximately US$1,000 for all materials and labour, or US$250/household. Conditions will vary according to each individual site and economies of scale were achieved with this system.

Table 1. Reedbed performance and key parameters (mean)

	Raw greywater	*1st Reedbed*	*2nd Reedbed*	*Pond*
Fecal coliform: cfu/100 mL	1.8×10^8 (±5.1 x 10^8)	6,300 (±7,500)	16 (±32)	52 (±50)
% removal		99.999%	99.99%	
BOD: mg/L	176 (±45)	7 (±2)	1 (±1)	3 (±2)
% removal		96.0%	99.4%	
Turbidity: NTU	104 (±38)	8 (±4)	2 (±2)	5 (±1)
% removal		92.3%	98.1%	

Note: All raw data rounded to nearest whole unit. Percentage removals are from raw greywater values.

RESULTS

Design considerations

The following design features for reedbeds for greywater treatment are as a result of this research.

Hydraulic Loading

The local water authority's design figure for domestic water supply is 150 litres/person/day with an average of six people per household. In a survey of water and wastewater conducted with the participating households in this project, the average total water consumption was 187 L/p/day with 4.5 people per household. The percentage of greywater was 60 to 70% of the metered water usage which equates to approximately 600 litres of greywater per day per household and represents approximately 75% of the total wastewater produced. A person equivalent (PE) figure for greywater of 121.5 L/day results (187 x 0.65). An allowance for rainfall needs to be made mainly to avoid flooding during heavy tropical downpours and evapotranspiration effects may also need to be determined if irrigation volumes are critical during the dry season. Evapotranspiration was measured as 4.4 mm/day during the dry season in Monteverde with the plant species and media material described in the following section.

Contaminant removal

The two reedbeds in series with the current greywater flow (approximately 755 L/day) achieve a level of treatment that exceeds the requirements of the Costa Rican standards for wastewater reuse on all samples. This was one of the objectives of this study. It is unlikely however that the system would have achieved the limits on fecal coliform if it had been receiving the volume of greywater originally estimated (2,500 L/day, 2.4 days HRT). Treatment by the first reedbed alone is sufficient to satisfy the BOD limit (BOD <40 mg/L) but insufficient to meet either of the fecal coliform limits (<100 or <1000 CFU/100mL). This has implications for the design of reedbeds for reuse in Costa Rica as fecal coliform limits will dictate minimum design criteria, in lieu of any other parameters such as nitrogen or phosphorus. Nutrient removal is likely to be limited in any event and where reuse for irrigation takes place these nutrients are beneficial. The first reedbed is treating approximately 755 L/day of greywater from seven people with a surface area of 16.8 m^2 with 4.5 days retention. This volume is approximately 100 litres less than would have been estimated using the PE figure of 121.5 L/day for seven people. On this basis however the first reedbed has a greywater PE of 2.7 m^2/PE (4.5 days HRT) and the total system 4.8 m^2/PE (7.9 days HRT) based on 6.2 person equivalents.

Organic loading

The organic loading on the total system averages 0.133 kg BOD/day or 44.3 kg BOD/ha/day. A mass loading rate of 112 kg BOD/ha/day is recommended as an upper loading rate which should not be exceeded (Crites and Tchobanoglous, 1998). If however only the first reedbed is considered a loading of 79.2 kg/Ha/day or 71% of the recommended limit results. Heavy organic loading particularly if not evenly distributed will cause odour which, in conjunction with the potential for clogging, has implications for inlet structure design described below.

Media

Gravel and crushed rock in the range of 5 to 35 mm nominal diameter are typically the media of choice and ideally are sourced as close to the reedbed site as possible to reduce transportation costs. Nevertheless the media material is likely to be the single most expensive component of the reedbed, and may in fact render a SSF system unviable (USEPA, 2000; WEF, 2001). The most suitable material for reedbeds in the Monteverde area is a crushed rock (approximately 20 mm diameter) which is available at a cost of US\$20/m^3. An alternative media using PET plastic bottle segments was trialed as part of this research and found to be equivalent and sometimes significantly superior in terms of contaminant removal to the local crushed rock (Dallas and Ho, 2004). A full-scale reedbed system consisting entirely of PET segments has now been functioning successfully for four years. The use of this material, packed in plastic onion bags for ease of handling and future maintenance, is demonstrated in Figure 1. The root growth into the PET media is shown after only three weeks in an experimental reedbed.
The properties of PET segments include an hydraulic conductivity in excess of 100,000 m/day, a porosity of approximately 94% and a density of 40 kg/m3. The advantages of PET include: a low cost, sometimes cost-free

media as it is a waste product; a very lightweight and easy to handle material which cut be cut into segments either by hand or mechanically; a media which is capable of providing a structurally sound substrate (capable of supporting a person's weight) once plant roots become established; and a significantly greater hydraulic retention time due to the high porosity. While the surface area available for biofilm development is initially low, our research found that significantly greater root development took place in PET-based systems compared to gravel-based systems and that superior contaminant removal performance was achieved once roots had become established. It is thought that this is a result of the greater surface area available in mature PET systems due to greater root mass, compared to gravel systems.

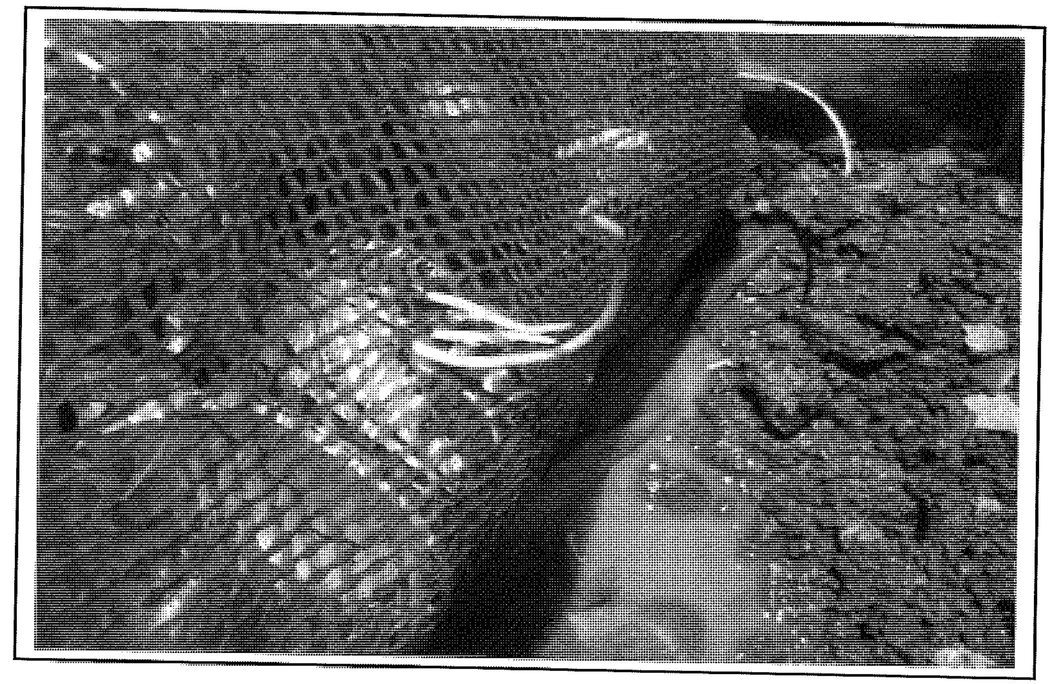

Figure 1. Root growth of *Coix Lacryma-jobi* after three weeks in PET-filled onion bags

Our studies found that when mature both types of reedbeds had suffered a loss of 20-30% in available volume primarily due to root growth, however PET systems still maintained over 60% greater available volume than crushed rock systems. This significantly greater retention time allows PET systems to achieve higher fecal coliform removal rates (Dallas and Ho, 2004).

The accumulation of solids in the media void space at the inlet is particularly detrimental to the hydraulic conductivity and it is recommended that larger sized media be used around the inlet zone to reduce the potential for clogging (Steiner, Watson et al., 1993). Some clogging although not severe is occurring at the inlet at this site and replacement of the gravel over the first 10% of the reedbed with sacked PET is being recommended.

Liner material

The soils of the Monteverde region are highly permeable and while clay exists at depth, its excavation and placement for domestic scale reedbed systems is uneconomic. Conventional liners are expensive and difficult to obtain. Ultimately a 'sandwich' design incorporating two layers of conventional builder's plastic (200µm) sandwiched between an inner and outer layer of geotextile was developed. These materials were cheap and easily available. Reedbeds were designed with length to width ratios (depth = 0.6m) which avoided the need for the plastic liner to be joined in any manner as experience had shown that any joints were prone to leakage. Rolls of conventional builder's plastic are nominally either 2.0 or 4.0 metres in width.

Plumbing and outlet structures

All systems were gravity-only which is feasible in hilly or mountainous terrain such as that in Monteverde and many other regions of Costa Rica. To further minimize cost and complexity all piping was kept to a minimum. Reedbed outlets were simply low points at the end of the reedbed. This avoided the need for any pipes to pass through the liner which we found to be a problematic detail and frequent source of leakage, as have others (Steiner and Combs, 1993). There are disadvantages of this arrangement however including limited water level control, water exits from the top rather than the bottom of the reedbed and an inability to drain the system if required. Where flow between two or more reedbeds or to a final stage polishing pond occurred, connections were by plastic lined gravel-filled drains.

Settling tanks and inlet structures

Pretreatment of the greywater prior to the reedbed is necessary to remove coarse and heavy solids as well as fat and grease. However the shortest possible retention of raw greywater to avoid the proliferation of anaerobic bacteria and hence odour, is advised. This is difficult to achieve without the use of a pump which we do not recommend. As a result our designs incorporate a settling tank of approximately one day's greywater production which usually consists of a locally available concrete culvert with poured concrete base. Sanitary "T"s are recommended at both the inlet and outlet pipe to avoid floating scum entering the reedbed. Womens' stockings have also been recommended (Jeppesen and Solley, 1994) as low-cost easily

replaceable filters for either the inlet or the outlet. De-sludging of the settling tank is however likely to be the most frequent, and unpleasant, maintenance issue which needs to be addressed. To enable de-sludging 75mm diamater scour pipe with external plastic valve and plastic mesh 'baskets' have been used or manual de-sludging is required. The amount of sludge build up is variable and it may be preferable to divert the high solids/grease kitchen greywater to the blackwater treatment system. Brandes (1978) in Jeppesen and Solley (1994) reported a sludge accumulation of 8.3 L/person/year in a greywater settling tank while the Western Australian Department of Health (2002) recommends an allowance of 40L/person/year which appears excessive in our experience. For ease of maintenance and improved distribution we recommend surface discharge using slotted pipe surrounded by large diameter media (usually 100-200 mm diameter rock) for the inlet structure.

Plants

Due to the region's steep topography, wetlands – and native wetland plants – are virtually non-existent. A species found growing locally - "Job's Tears" (*Coix lacryma-jobi*) – was trialed due to its deep penetrating root system which has the desirable effect of creating maximum contact with wastewater (Brix, 1997). Reedbeds have been planted at an initial density of approximately three to four plants/m^2 which has increased to six to seven plants/m^2 when mature. Our research over four years has shown *Coix lacryma-jobi* to be a resilient and viable emergent species in reedbed systems for both greywater-only as well as combined black and greywater treatment.

Maintenance

The maintenance of owner-maintained greywater systems is a significant issue and may well dictate the sustainability of such systems for domestic purposes. A pilot project on greywater reuse conducted by the City of Los Angeles found that 80% of the systems trialed were not maintained by their owners, even when the maintenance involved the simple cleaning of filters and where all the participants had volunteered for the project (Jeppesen and Solley, 1994). To ensure a sustainable maintenance program for the four-household greywater reedbed treatment system described here an environmental services contract (ESC) was drawn up (CEDARENA, 2001). This allows the owner upon whose property the reedbed is located to receive monthly payment for the provision of this service from those neighbours connected to the system. While the tariff is small (US$0.30/month/household) it represents the first environmental services contract of its kind for the provision of private wastewater treatment in Costa Rica (Jiménez, 2002). The maintenance of these reedbed systems principally consists of the regular de-sludging of the settling tank and any greasetraps. Other maintenance issues include occasional weeding, pruning of overhanging branches so as to maximize sunlight to the reedbed and the thinning of aquatic plants in cases where a final polishing pond is used.

Costs

The cost of installation of a reedbed for a typical single household is given in Table 2 and is based upon materials only and the use of crushed rock as the reedbed media material.

Design criteria:

Q = 600 L/day, Hydraulic retention time (HRT) = 5 days

Dimensions of reedbed: L = 5.8m, W = 2.6, D = 0.6m, A = 15m^2, L:W = 2.2:1

Properties of media: Assumes porosity of 40%, longterm hydraulic conductivity of 100 m/day minimum. Bed slope of 0.5%

Table 2. Installation cost (excluding labour) for a typical domestic reedbed for greywater treatment

Cost	*Geotextile*	*Liner*	*Crushed rock*	*Plumbing*	*Settling tank*	*Total materials (US$)*
No. units	60 m^2	60 m^2	8 m^3	12 lm	1 x 500L	
US$/unit	1	0.50	20	5	40	
Total	**60**	**30**	**160**	**60**	**40**	**350**

Note: Dollars US (2003). Plumbing costs will vary according to site - figure given is approximate.

The fact that the crushed rock represents 46% of the total materials cost for this reedbed highlights the cost saving potential of PET as an alternative media. A retention time of five days was chosen as fecal coliform and BOD removal rates have been observed to deteriorate rapidly for retention times less than four days (Dallas and Ho, 2004).

CONCLUSIONS

This research has demonstrated the viability of simple, low cost reedbeds for domestic greywater treatment in the mountainous regions of Costa Rica. Further, that it possible to install these systems at a cost several times less than for a comparable system in the US. Reductions of fecal coliform greater than 99.999% were achieved with a retention time of 4.5 days however this

was insufficient to meet the national wastewater reuse limit of <1,000 cfu/100 mL. The use of PET segments as a low-cost alternative to gravel for reedbed media was demonstrated. PET media is able to increase retention times by upto 60% over conventional gravel-based SSF systems, is lightweight and easily handled and can displace an otherwise non-renewable resource. PET bottles are a readily available waste product in most parts of the world and their use has the potential to greatly reduce the cost of subsurface flow constructed wetlands. Further research on this material in greywater-only and mixed wastewater fed reedbeds is currently being undertaken. The use of locally available materials without the need for specialist equipment is paramount for the sustainability of low-cost appropriate technologies. Community acceptance is also paramount. Awareness and uptake of this technology for greywater treatment described here has been demonstrated by the sponsoring of four of the five reedbeds currently in Monteverde by either individuals or organizations. Maintenance is a key issue for domestic wastewater treatment systems that do not fall within the municipal responsibility. The environmental service contract developed as part of this research is one method through which funding for on-going maintenance can be achieved, nevertheless the need to incorporate low maintenance features at the design stage cannot be underestimated.

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